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Evaluating the relationships among economic growth, energy consumption, air emissions and air environmental protection investment in China

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A B S T R A C T

This paper analyzed the interactions among China's economic growth and its energy consumption, air emissions and air environmental protection investment during 2000–2007. Conventional energy and emergy are applied to quantify energy consumption and emissions' impact, respectively. The five indicators based on money, energy and emergy, including ratio of nonrenewable energy to renewable energy (RNR), energy use per unit GDP (EUPG), environmental cost per unit GDP (ECPG), impact of emissions per unit energy consumption (IEPEC), and environmental benefit per unit environmental protection investment (EBPEI), are presented to depict the relationships among economic growth and energy consumption and impact of air emissions and air environmental protection investment. The results show that energy consumption rapidly rises with China's fast economic growth; however, energy efficiency and environmental loading intensity from energy consumption are reduced simultaneously but their improvements fall far behind economic growth rate. Impact of air emissions, mainly composed of impact of emissions on human health (especially dust), is slightly decreased. The performance of air environmental protection investment is obviously declined in the study period. Generally speaking, the conflict among economy, energy and air environment protection is slightly mitigated but still acute due to great dependence of China's economy on fossil energy and inefficient environmental protection measures. Finally, this paper discusses the corresponding issues, and then puts forward some related suggestions.

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1. Introduction

World has seen huge changes in economic and social and environmental scopes in China due to the great reform and transition during the past thirty years. Chinese economic system has begun to transform from planned economy to market economy since the Third Plenary Session of the Eleventh Central Committee [1]. China has been enjoying the world's fastest economic growth by a 10.6% annual growth rate of gross domestic production (GDP) or a 9.5% annual growth rate of per capita gross domestic production (per capita GDP) since the 'Open Door Policy' in 1978 (See Fig. 1.), in comparison with the world's average of 3.3% during the same period, and the rapid economic growth has greatly raised China's economic status in the world [2,3]

The rapid economic growth of China has triggered fast-growing energy consumption (especially fossil energy), which observably raised China's dependency on oil imports [4]. This will further threat energy security of China due to the vulnerability of its immediate energy supply and the lagging safeguarding system for energy security. On one hand, the rapid growth of energy demand has growing pressure on energy supply. One report from Chinese Academy of Science predicts that the total energy demand amount will reach 2.89–3.88 billion tonnes standard coal equivalents in 2020. At that time about 0.32–1.17 billion tonnes coal will not be satisfied from home market, and especially there will be massive gaps in petroleum and natural gas supply. On the other hand, the increasing dependence on abroad energy market is also challenging Chinese economic security. In 2009, the output of Chinese crude oil was only 1.89×10^8 t or so, and about 1.89×10^8 t was imported from abroad. Therefore, crude oil interdependency of China on abroad market was nearly 50%, which hit the international warning line of 50%. According to "blue book on energy" published in 2009, crude oil interdependency of China on abroad market will be about 64.5% 10 years later. However, China has not won the pricing right of energy sources in the world. So Chinese energy security will have to face more challenges from abroad and will become the core issue affecting the sustainability of Chinese economy [5].

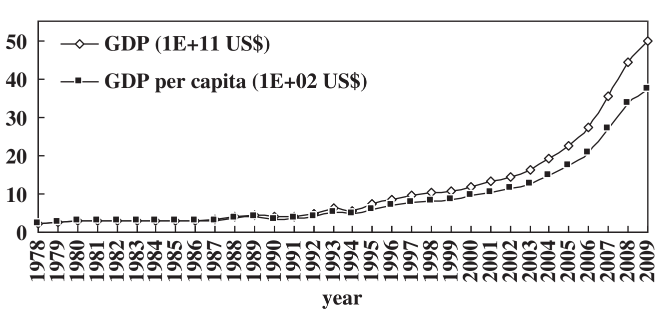


Fig. 1. Trends of GDP and per capita GDP of China during 1978–2009 (From this study).

Furthermore, the production and consumption of nonrenewable energy resources have led to serious environmental problems in China [6–8], which has attracted worldwide attention due to the global economic and environmental effects of its rapid economic growth and the country's accelerating energy consumption during the last 30 years [9]. Therefore, energy conservation and pollution control have been further accentuated in the "Eleventh five-year plan" with a target of cutting energy consumption per unit of GDP by 20% and pollutant discharges by 10% from 2006 to 2010 [4].

Meanwhile, Chinese central government has implemented a serial of environmental management systems during this period. Therein, he "32 words" guidelines were put forward in the first conference on environment protection held in 1973, which include "comprehensive planning, proper redistribution, multipurpose use, turning harm into good, relying upon the masses, everyone taking action, protecting environment, benefiting the people". Environmental protection was established as the basic state policy of China in 1982. One year later, "synchronous development guidelines" were established, which included "Economic Construction, Municipal and Rural Construction and Environment Construction should be synchronously planned, synchronously implemented and synchronously developed so as to unifying economic benefit and social benefit and environmental benefit." They can be regarded as the general principle and policy of Chinese environmental protection because they point out how to correctly deal with the relationships environmental protection and economic development. Another environment protecting policy system containing three policies and eight systems was formed in the third National Environmental Protection Conference held in 1973. The three policies include the policy of focusing on prevention and combining prevention with controlling, the policy of "polluter pays", and policy of tightening up environmental management. The eight systems include Environmental Impact Assessment System, Comprehensive Realignment System on Urban Environment, "Three Simultaneities" System.[1] Pollutants Discharge Fee System, System of Environment Objectives Accountability; Pollutants Discharge License System; System of Undertaking Treatment within a Prescribed Limit of Time; Centralized Controlling System. The three policies and eight systems embody the basic state policy of environmental protection and the "synchronous development guidelines", and they were the important mark that Chinese environmental management system became mature. Next sustainable development was established as an national development strategy and it has become the general guideline for each domain in "the Ninth Five-Year Plan for National Economic and Social Development and the Outline for the Long-Range Objective Through the Year 2010" promulgated in 1996 [10]. In addition, China has gradually enlarged environmental protection

[1] "Three Simultaneities" system is one of Chinese environmental protection systems, and it means that when a construction project is implemented, its facilities for environmental protection must be designed, constructed, and put into use simultaneously with its production facilities of the project.

investment, and environmental investment GDP ratio increased from 0.7% in the Seventh Five-Year Plan period to exceed 1% nowadays, with a rapid growth in recent years [11]. However, it is not clear that how much those countermeasures have contributed to China's pollution control.

So far, many scholars have carried out a large numbers of researches on China's economy and environment and energy, such as energy and resource account [6,12–16] and their efficiency [12,17,18], the relationship between China's economic growth and energy consumption [19], the relationship among China's economic growth and environment [20], energy and environment [21–26], the relationship among China's economic growth, energy consumption and environment [27–29], the relationship among China's energy consumption, environmental protection measures and environment [30], sustainability of Chinese social economy [13,31–34], etc. However, those researches are lacking in analyzing emissions' impact and/or the interactions among economy, energy, emissions, and environmental protection investment. The quantity and quality scarcities of the diverse flows require a more efficient, effective and interdependent utilization based on overall and unified accounting.

Emergy, created by Odum, is defined as the sum of the available energy (exergy) of one kind previously required directly and indirectly through input pathways to make a product or service [35]. This method has been widely accepted as an effective ecological evaluation tool and applied to different scale ecosystems, such as macro-ecosystems related to geobiosphere and nations [36–50], regions [45,51–54], urban areas [55–63], islands [48], dams and river diversions [64–67], production systems [68–79], environmental protection engineering [80,81]. Recently, some scholars have also made the related researches to improve emergy approach, such as improving emergy accounting [82–88], assessing impact of emissions through emergy approach [89,90], measuring and assessing carry capacity of environment in a region [91], updating some of unit emergy values [92–94], joint use of emergy approach and other methods [70,95–98], etc. Those studies have greatly enriched research contents of traditional emergy approach and promoted its development; however, it is still necessary to further enlarge the research fields of emergy approach in order to fully explore its potential, such as emergy analysis of the performance of environmental protection investment, etc. Meanwhile, more other methods should be integrated into emergy approach to make up for its shortcomings.

China's fast growing economy is based on great deal of fossil energy consumption, which in turn leads to a large number of air emissions. Those serious energy and environmental issues have driven a great deal of investment in air environmental protection field in China. However, how about the interactions among China's economy, energy, air emissions and air environmental protection investment? How about the impact of air emissions and the performance of air environmental protection investment? These issues should be investigated through a comprehensive method so as to reveal the potential conflicts during China's rapid economic growth against historical background. This paper aims to applying emergy analysis method and several corresponding indicators to exploring the relationships among China's growing economy, energy consumption, impact of air emissions, and air environmental protection investment from 2000 to 2007 so as to provide a new perspective and some helpful suggestions for policy-makers. Emergy is used to quantify emissions' impact; the corresponding indicators based on emergy and energy and money units are adopted to assess the interrelationships among GDP growth, energy consumption, and impact of air emissions and air environmental protection investment. Detailed systematic indicators are examined from a time serials, and temporal variation of indicators are explored to illustrate some characteristics of the Chinese economy. Finally, this paper discusses the related issues and puts some corresponding suggestions.

2. The relationships among economic growth, energy consumption and atmosphere environment

Energy is the driving force of economic growth. Energy consumption causes air emissions, and this leads to all kinds of impact on people and environment, such as harming human health, affecting other species' survival, consuming environmental self-purification ability, etc; in turn, this will affect economic sustainable growth. Facing this conflict, mankind has to invest in air environmental protection field so as to mitigate this adverse impact. The relationships among economy, energy, air emissions and environment are illustrated in Fig. 2. It is found that the key core issue is to keep a dynamic balance among economic growth, energy consumption and air emissions for sustainable development.

3. Methods

3.1. Introduction of emergy analysis method

In order to fully integrate the values of energy, materials, and information in a common unit, an ecological evaluation approach based on emergy was firstly presented by Odum in 1983, out of a creative combination of energetics and systems ecology [35,36,99,100]. Emergy was created to evaluate the work previously done to make a product or service [35,36]. It represents all the work given by the environment to sustain a certain system and produce a certain level of output. As a measure of energy used in the past, emergy analysis is totally different from the conventional energy (with unit joule) analysis that merely accounts for the remaining available energy at present, which is therefore proved to be a feasible approach to evaluate the status and position of different energy carriers in the universal energy hierarchy, and it has been widely accepted as an effective ecological evaluation tool.

Emergy is expressed with the unit solar energy joule (sej) which is employed as the equivalent to measure different quantities and qualities of energy and materials. Transformity and

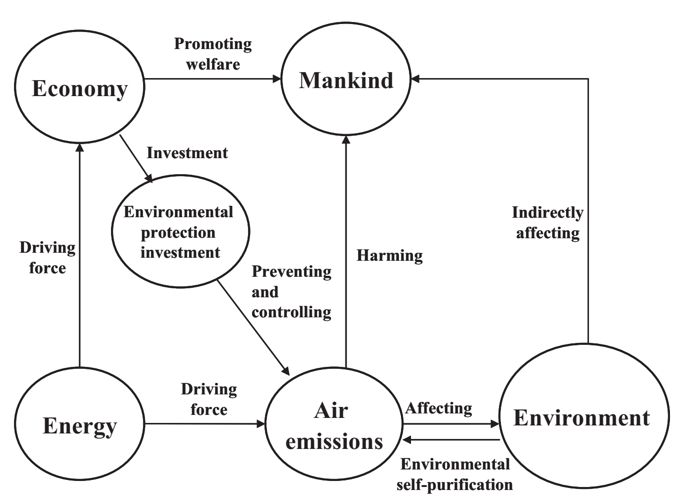


Fig. 2. the relationships among economy, energy, air emissions and environment.

other unit emergy values are proposed to determine the universal hierarchical position of the energy and materials, which is the fundamental characteristic of emergy analysis. The global empower base 15.83E24 sej/y [101] was used as the basis for calculating the emergy of impact of emissions in this study. Three emergy baselines have been used in recent emergy studies [102]: the first one is 9.44E24 sej/y [36], the second one is 9.26E24 sej/y [103], and the third one is 15.83E24 sej/y [101]. Results from existing studies of emergy intensity were converted to the 15.83E24 sej/y baseline through multiplying by the appropriate factors (1.68 (15.83/9.44) for the 9.44 E24 sej/y baseline or 1.71 (15.83/9.26) for the 9.26 E24 sej/y baseline).

3.2. Quantifying emissions' impact

Emissions from economic activity can harm the ecosystem, people, and the economy; they may require emergy to render them harmless [104], which can be done by diluting or degrading the emissions to an acceptable concentration or state.

3.2.1. Ecological services needed to render emissions harmless

This emergy to absorb impact may be derived from both ecological and economic sources. Many emissions are rendered harmless due to services provided by the ecosystem which dilute or degrade the emissions to an acceptable concentration or state. The emergy for these ecological services may be determined from knowledge of the concentration and nature of the emissions, and the transformity of the relevant ecological services.

We calculate the ecological services for diluting emissions according to the research of Ulgiati and Brown [105]. Here, we consider the air emissions in the economic activity. Although they have been treated before being released into environment (In fact, some of them have not been treated at all), the emission concentrations of some of them are still higher than the corresponding environmental quality standards. Therefore, the ecological services are needed to reduce their concentrations to the acceptable level. The ecological services includes all kinds of environmental self-purification, composed of physical, chemical and biological processes, and it is often the last step of pollution controlling because it is very difficult for all production processes to achieve complete zero emissions. Here we consider only environmental dilution.

Ecological services for diluting air pollutants can be computed as follows: first, the mass of extra air required to dilute each emission can be attained according to

$$M = d \times (W/C) - M_{air} \quad (1)$$

where M is the mass of extra air for diluting one kind of air emission; M_{air} is the mass of discharged air from economic activity; d is air density; W is the mass of the corresponding emission from economic activity; c is the acceptable concentration from agreed regulations (See Table 1.).

Table 1
the considered air pollutants' accepted concentrations a.

Pollutants' name	Acceptable concentration (mg/m^3)	References
Dust	0.08	[108]
SO_2	0.02	[108]

[a] The concentrations in the first grade level in the corresponding environmental quality standards are regarded as the related pollutants' acceptable concentrations for the fact that they are the safest for human and environment.

Then, the energy value of required environmental services is determined, by calculating the kinetic energy of the extra air for diluting one kind of emission, using annual average value for wind speed in a country (Here, the annual average value for wind speed is 2.24 m/s [106]. This energy is a measure of the wind energy needed to dilute the pollutant. Finally, when multiplied by the wind energy transformity 2.45E+03 sej/J [107], it gives a measure of the environmental service that is required, in units of emergy.

3.2.2. The emergy loss caused by emissions

Some emissions may harm the ecosystem by causing a fish kill, lake eutrophication, etc; and they also lead to economic loss by harming human health, land occupation, etc. Such effects may be quantified as the emergy contained in the ecological and economic loss. Many studies have estimated the monetary loss of environmental impact. This may be easily converted to emergy via the emergy/money ratio.

Quantifying the ecological impact in terms of emergy requires knowledge about the loss of ecosystem components and self-organization caused by the emissions [109]. Ecological impact is represented by the potentially affected fraction or potentially disappeared fraction of species in the affected ecosystem [110]. The output of a LCIA approach such as eco-indicator 99 may be converted to a corresponding exergy loss or emergy input. Here the ecological losses caused by emissions were not considered due to lacking the corresponding data.

We calculated the economic loss caused by emissions according to the references [111,112]. The loss comes from impact of air pollutants on human health.

Impact of air pollutants on human health includes respiratory disorders, climate change, etc [112]. Disability adjusted life years (*DALY*) measures the impact on human well being [110]. This represents the years of life lost and years lived disabled due to the emissions' impact, and it is based on an approach developed by the World Health Organization (WHO).

One *DALY* can be thought of as one lost year of "healthy" life. The sum of these *DALYs* across the population, or the burden of disease, can be thought of as a measurement of the gap between current health status and an ideal health situation where the entire population lives to an advanced age, free of disease and disability.

DALYs for a disease or health condition are calculated as the sum of the Years of Life Lost (*YLL*) due to premature mortality in the population and the Years Lost due to Disability (*YLD*) for incident cases of the health condition. The basic formula for *DALY* is the following for a given cause, age and sex:

$$DALY = YLL + YLD \quad (2)$$

The *YLL* basically correspond to the number of deaths multiplied by the standard life expectancy at the age at which death occurs. The basic formula for *YLL* is the following for a given cause, age and sex:

$$YLL = N \times L \quad (3)$$

where: N: number of deaths; L: standard life expectancy at age of death in years.

Because *YLL* measure the incident stream of lost years of life due to deaths, an incidence perspective is also taken for the calculation of *YLD*. To estimate *YLD* for a particular cause in a particular time period, the number of incident cases in that period is multiplied by the average duration of the disease and a weight factor that reflects the severity of the disease on a scale from 0 (perfect health) to 1 (dead). The basic formula for *YLD* is the following:

$$YLD = I \times DW \times L \quad (4)$$

Table 2
Several air emissions, immediate destination of emissions and impact categories (coming from the reference [112], and corrected according to the emergy baseline 15.83 [101]).

Pollutants' name	Immediate destination of emissions	Impact categories considered	DALY/Mt of emissions	ECEC/Mt of emissions (sej/Mt)
SO_2	Air	Respiratory disorders	5.46E04	3.12E21
Dust	Air	Respiratory disorders	3.75E05	2.15E22
CO_2	Air	Climate change	2.1E02	1.20E19

where: *I*: number of incident cases; *DW*: disability weight; *L*: average duration of the case until remission or death (years).

The other details of *DALYs* see the Web of WHO.[2]

Table 2 lists several air pollutants considered in this work, the impact categories they belong to and corresponding *DALY* values per million tonnes of emissions. Ukidwe and Bakshi [113] discussed the approach for converting *DALYs* to ecological cumulative exergy consumption (*ECEC*). Human health impact of emission measured in *DALY* can be converted to *ECEC* using the following equation.

$$C_j = m_j \times DALY_j \times \tau_{HR} \tag{5}$$

here, m_j: the mass rate of emission of substance *j*; $DALY_j$: the corresponding *DALY* value; τ_{HR}: the transformity of human resource, which is obtained by dividing total emergy budget of a nation by the total population of this country; C_j: the impact of emission on human health.

ECEC is an extension of industrial cumulative exergy consumption to include ecosystems, and it becomes equivalent to emergy if the analysis boundary, allocation approach, and method for combining global energy inputs are identical. In fact, value of *ECEC* is generally equal to emergy value for a given substance because they are both calculated through transformities or specific emergy [114]. Then we can obtain the emergy value of emissions' impacts on human health according to *ECEC* values of emissions. This study just considers the three kinds of air emissions indicated in Table 2.

3.3. The indicators depicting the interactions among economic growth and energy consumption, emissions and environmental protection investment

Economic development is driven by all kinds of energy resources which are generally defined as anything that can be used as a source of energy, including renewable and nonrenewable ones. Access to energy resources is vital to economic development and prosperity, and energy resources will become a constraint to economic development when not insufficient or available. Therein, renewable resources which are replaced rapidly by natural processes, have low or no emissions during the use stage; however, nonrenewable energy resources which are not replaced or replaced only very slowly by natural processes, produce a large number of emissions during the course of consumption. And all kinds of emissions due to energy consumption can affect environmental quality when they exceed environmental capacity. In return, the deterioration of the environmental quality threatens the existence of mankind and economic development. Therefore, there exist mutual influences between economic development and energy consumption and emissions. The following indicators are applied to depict the interactions among economic growth and energy consumption and emissions.

(1) Ratio of nonrenewable energy to renewable energy (*RNR*): *RNR* refers to the ratio of energy of nonrenewable resources to that of renewable energy resources. This indicator reflects the energy mix. The bigger the indicator, the greater the dependence of economic activity on nonrenewable energy resources is. This case can lead to the more emissions when all other conditions keep constant.
(2) Energy use per unit GDP (*EUPG*, J/US$): *EUPG* equals the energy of total energy consumption divided by GDP. The higher the indicator, the lower the energy efficiency of economic activity is. The indicator is mainly affected by energy mix and technical progress. High share of renewable energy and/or advanced technology are helpful to enhancing energy efficiency of economic activity. Compared to those traditional energy intensity indicators for measuring economic activity, such as tonne of standard coal equivalents per unit GDP, tonne of oil equivalent per unit GDP, etc., this indicator is more convenient for comparing and trace the energy efficiency of different countries or regions.
(3) Environmental cost per unit GDP (*ECPG*, sej/US$): it is the ratio of the total emergy loss caused by emissions to GDP. This indicator measures environmental cost of emissions in terms of emergy. The bigger the indicator, the larger the environmental cost of economic activity is. The indicator is mainly affected by industrial structure, technical progress and environmental protection measures. High share of highly polluting industries, backward technology and ineffective environmental protection measures can lead to big *ECPG* values.
(4) Impact of emissions per unit energy consumption (*IEPEC*, sej/J): *IEPEC* is the ratio of the emergy of emissions' impact to the energy of total energy consumption. It reflects environmental loading intensity of energy consumption. The bigger the ratio, the higher the environmental loading intensity of energy consumption is. This indicator is mostly affected by technical process, energy structure and environmental protection measures. Advanced technology and environmental protection measures and high share of renewable energy resources can reduce *IEPEC* value.
(5) Environmental benefit per unit environmental protection investment (*EBPEI*, sej/US$): *EBPEI* is the ratio of emergy of impact of reduced emissions to the related environmental protection investment. This indicator reflects the efficiency of environmental protection investment. The bigger the indicator, the higher the efficiency of environmental protection investment is.

In this paper, data on China's GDP came from China Statistical Yearbook [115]. The components of energy consumption were mainly composed of coal, petroleum, natural gas, hydroelectricity, and nuclear power. Data on energy came from China Statistical Yearbook [115]. Other energy sources are not considered due to lacking the corresponding data in most years. The air emissions mainly included CO_2, SO_2, and dust. Air emission data came from U.S. energy Information Administration Independent Statistics and Analysis [116], China Statistical Yearbooks [117], Gu's doctoral dissertation [118], the research of Wang and Chen [119], and Zhu's doctoral dissertation [120]. Data on total waste gas discharge came from China Statistical Yearbook [117], the research of Wang and Chen [119], Gu's doctoral dissertation [118] and Zhu's doctoral dissertation [120]. And the value of annual average wind speed came from the research of Reng et al. [106]. The tansformity of wind energy is 2.45E+03 sej/J [107]. The whole country, except Hongkong, Macao and Taiwan, was chosen as the boundary of the analysis.

[2] Worth Health Organization (WHO). Metrics: Disability-Adjusted Life Year (DALY). http://www.who.int/healthinfo/global_burden_disease/metrics_daly/en/index.html.

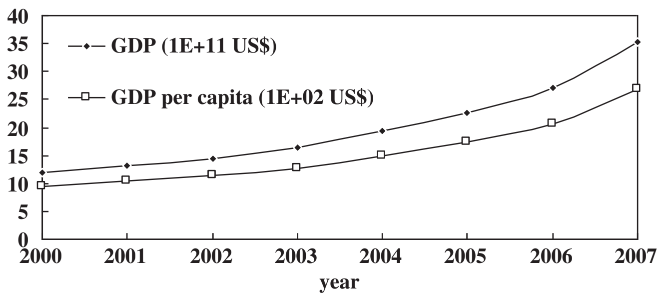


Fig. 3. Trends of GDP and per capita GDP of China during 2000–2007.

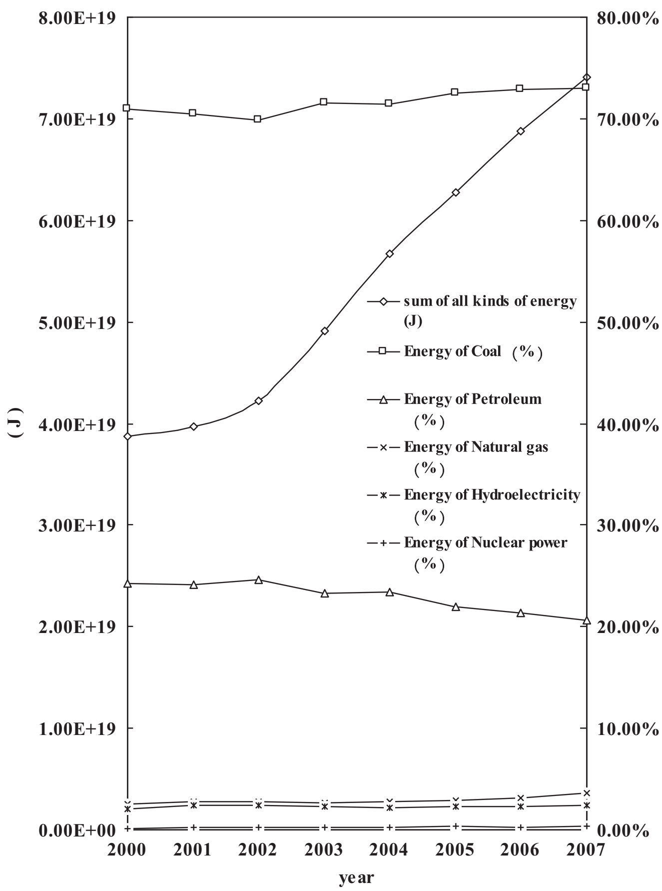


Fig. 4. Trends of energy consumption and its structure in China during 2000–2007.

4. Account

4.1. GDP and per capita GDP

As shown in Fig. 3, GDP and per capita GDP were raised by 1.95 times and 1.83 times from 2000 to 2007 and they were continuingly increasing by an annual growth rate 16.72% and 16.00%, respectively during this period.

4.2. Energy consumption and its structure

As illustrated in Fig. 4, energy consumption grew by 90.98% from 2000 to 2007, with an annual growth rate of 9.68% during this period. Therein, the annual mean percents for coal, petroleum, natural gas, hydroelectricity, and nuclear power were 71.58%, 22.98%, 2.90%, 2.28%, and 0.26%, respectively; the annual percents of coal, natural gas, hydroelectricity, and nuclear power slightly climbed while the annual percent of petroleum declined a little in the study period.

4.3. Impact of emissions

4.3.1. Ecological service used to dilute the emissions

As illustrated in Fig. 5, ecological service used to dilute air pollutants rose by 13.86% from 2000 to 2007, with an annual growth rate of 1.87% in this period. On the average, 81.55% and 18.45% of ecological service were consumed to dilute SO_2 and dust, respectively in the study period. Generally, annual mean percent of ecological service used to dilute SO_2 climbed by 9.66% while annual mean percent of ecological service used to dilute dust dropped by 33.92% in this period.

4.3.2. Emergy loss caused by emissions

As shown in Fig. 6, emergy loss caused by air pollutants decreased by 10.37% from 2000 to 2002, and increased by 13.83% from 2002 to 2005, and declined by 12.15% from 2005 to 2007, with an annual decline rate of 1.55% from 2000 to 2007. Therein, emergy loss caused by dust, SO_2 and CO_2 had annual average percents of 86.42%, 12.59% and 9.99% in the study period. Annual percents of emergy loss caused by SO_2 and CO_2 grew by 38.50% and 158.40%, respectively while annual percent of emergy loss caused by dust dropped by 16.58% in this period.

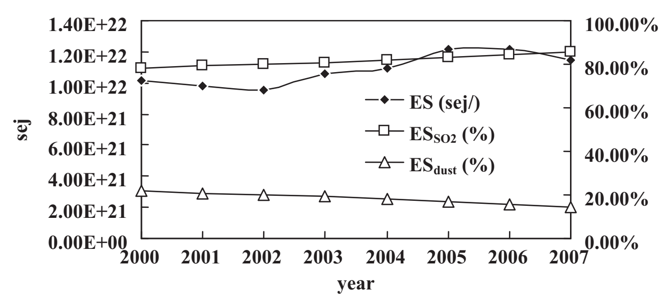


Fig. 5. Trends of ecological service and its structure of China during 2000–2007. Therein, ES: Ecological service used to dilute air pollutants; ES_{SO_2}: Ecological service used to dilute SO_2; ES_{dust}: Ecological service used to dilute dust.

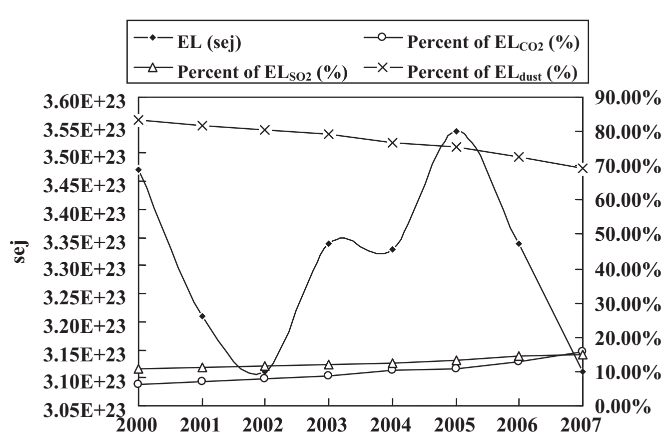


Fig. 6. Trends of emergy loss from air emissions and its structure in China during 2000–2007. Therein, EL: Emergy loss caused by air pollutants; Percent of EL_{SO_2}: Percent of emergy loss caused by SO_2; Percent of EL_{CO_2}: Emergy loss caused by CO_2; Percent of EL_{dust}: Emergy loss caused by dust.

4.3.3. Emissions' impact

As illustrated in Fig. 7, impact of emissions from air pollutants decreased by 10.08% from 2000 to 2002, rose by 14.02% from 2002 to 2005, and decreased by 11.75% from 2005 to 2007, with an annual decline rate of 1.42% during the study period. Therein, emergy loss and ecological service had annual average percents of 96.82% and 3.18%, respectively in the study period. Annual percent of emergy loss declined by 0.76% while annual percent of ecological service grew by 26.15% in the study period.

5. Results and analysis

5.1. RNR

As illustrated in Fig. 8, this ratio declined by 15.25% from 2000 to 2002, increased by 10.90% from 2002 to 2004 due to production shifting towards more energy intensive sectors [121], and decreased by 7.64% from 2004 to 2007 due to carrying out a serial of effective measures since the 11th Five-Year Plan [122], with an annual average decline rate of 2.00% in the study period. Generally speaking, the energy structure was slightly improved in fluctuation in the study period.

5.2. EUPG

As shown in Fig. 9, this indicator declined by 9.91% from 2000 to 2002, and decreased by 23.37% from 2002 to 2007, with an annual decline rate of 5.15% in the study period. The fluctuation of the indicator between 2001 and 2004 may lie in the increased use of energy-intensive technology [123]. However, generally the energy efficiency of China was improved in the study period. This achievement is mainly attributed to changes in the structure of final demand especially in the later period [124], which generally exceeds negative impacts of production shifted to heavy energy-consuming sectors after 2002.

5.3. ECPG

As illustrated in Fig. 10, this indicator decreased by 67.58% from 2000 to 2007, with an annual decline rate of 14.86% in this period. This means that the environmental cost caused by air emissions was obviously reduced in this period. When viewed in absolute terms, it cannot be denied that China's pollution

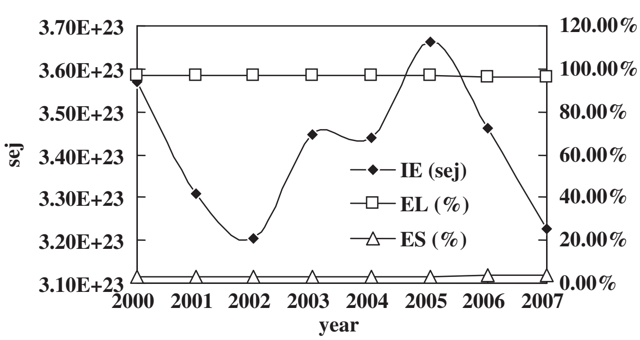


Fig. 7. Trends of impact of air emissions and its structure of China during 2000–2007. Therein, IE: Impact of emissions from air pollutants; EL: Emergy loss caused by air pollutants; ES: Ecological service used to dilute air pollutants.

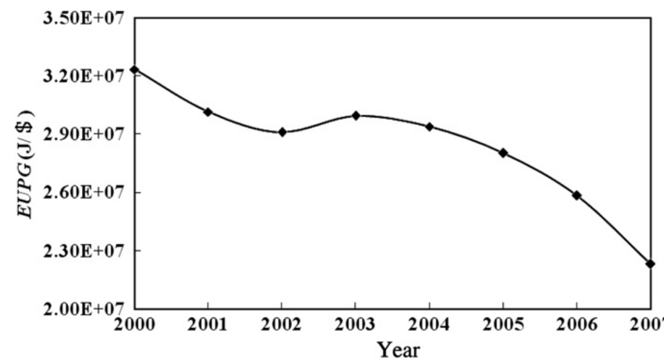


Fig. 9. Trends of energy use per unit GDP (*EUPG*) of China during 2000–2007.

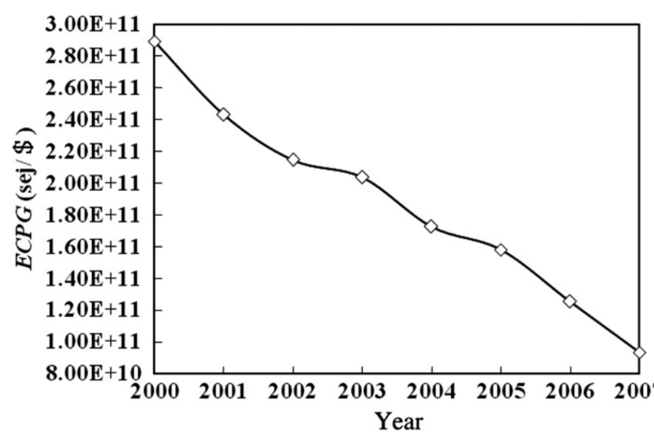


Fig. 10. Trends of environmental cost per unit GDP (*ECPG*) of China during 2000–2007.

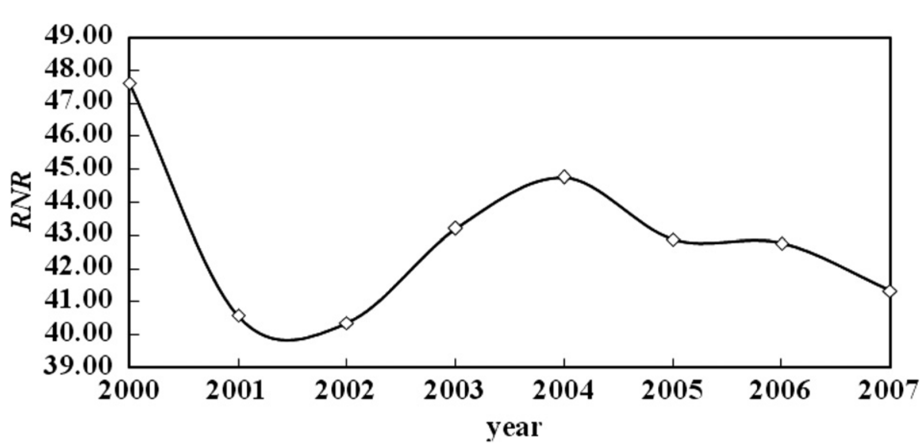


Fig. 8. Trends of ratio of nonrenewable energy to renewable energy (*RNR*) of China during 2000–2007.

situation remains quite serious, but the results show that the country has been moving in the right direction in recent years. The introduction of these advanced technologies, including flue gas desulfurization, wind power generation, and high efficiency coal-fired power generation, have contributed obviously to reducing air emission intensity per unit GDP in the period [125]. Accompanying with increasing air environmental protection investment, Chinese companies acquired large shares of the market soon after such technologies were introduced from overseas and started to spread. The greatest weapon for Chinese companies to expand their market share is their cost competitiveness. These cost savings have added to the momentum after the introduction of these technologies, and have led to the rapid development of energy conservation and environmental measures in recent years.

5.4. IEPEC

As shown in Fig. 11, this indicator decreased by 52.61% from 2000 to 2007 except a slight fluctuation between 2003 and 2005 due to economic structure worsening and ineffective management instruments, with an annual decline rate of 10.12% in the study period. This shows that environmental loading intensity of energy consumption was greatly reduced in this period. At the same period, the State Council convened two national environmental protection conferences. Therein, the Fifth National Environmental Protection Conference held in 2002 planned environmental protection work for the “10th Five-Year Plan”, emphasizing that environmental protection is one of the important functions of the government. Notwithstanding, the targets of environmental protection for the “10th Five-Year Plan” was not fulfilled due to the reason of irrational economic structure and rough mode of economic growth, as well as slack enforcement and ineffective supervision and monitoring [126]. Because of this, the State Council convened the Sixth National Environmental Protection Conference in April 2006, in which Premier Wen Jiabao emphasized “synchronization” and “equal importance” of environmental protection and economic development and required to resolve environmental problems through “comprehensive” measures, by which environmental protection has been put on a more outstanding and strategic position. Energy saving and emission reduction were made the restrictive obligation in the “11th Five-Year Plan”, which also emphasized the environmental protection responsibility and therefore brought about new hope for the solution of environmental problems. China’s energy policies give priority to the reduction and rehabilitation of environmental damage and pollution resulting from energy development and

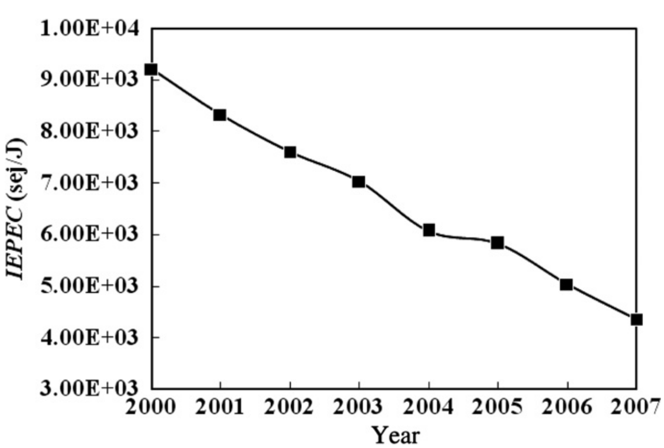


Fig. 11. Trends of impact of emissions per unit energy consumption (*IEPEC*) of China during 2000–2007.

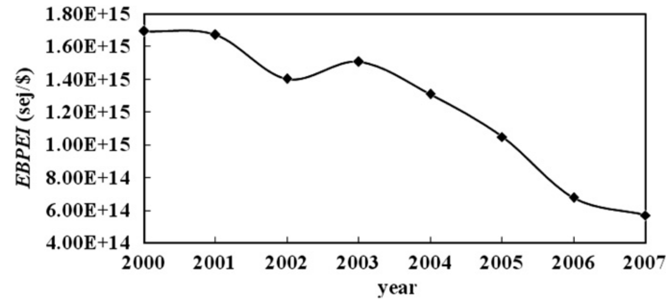


Fig. 12. Trends of environmental benefit per unit air environmental protection investment (*EBPEI*) of China during 2000–2007.

utilization. Those policies have promoted energy saving, slight improvement of energy structure (Fig. 4) and the growth of air environmental protection investment. Next years, a number of air environmental protection facilities were installed in energy industry. Finally, these measures obviously cut air emission intensity of energy sections.

5.5. EBPEI

As shown in Fig. 12, this indicator decreased by 66.27% from 2000 to 2007 except 2003, with an annual decline rate of 14.38% in the study period. This means that the efficiency of air environmental protection investment abruptly declined in the study period. Adequate environmental economic policies can stimulate enterprises to install high-efficiency air pollution control installations. Therein, emission charge and trading system is regarded as one of the most cost-effective economic policies. China has now completed the piloting of SO_2 emission trading in Henan, Shanxi, Shandong, etc. But, most of the trading cases were achieved under the intervention of local governments, and it is far away from a totally marketed system. According to the new Rules on Pollution Discharge Charging approved by the State Council of China in 2004, enterprises were charged 0.6 Yuan RMB per ton of SO_2 or NO_x emissions starting July 1, 2005. However, it is still lower than the cost to install high-efficiency de-dust/SO_x/NO_x control facilities. So, the levy charging on air pollutant emissions should be increased further in order to push the enterprises installing advanced control facilities, such as FGD, advanced low NO_x combustion systems, and even SCR in coal-fired power plants. Also, adequate economic policies can promote the R&D of new technologies. With the economic development, a greater amount of coal production in China will be fueled for coal-fired power generation, and thereby large amounts of SO_2 and NO_x will be produced. The uneven distribution of SO_2/NO_x emissions and the resulting acid rain by provinces, indicates that it is not cost effective and realistic if all the sources are regulated to the same level and are equipped with high-efficiency control devices. It may be a cost-effective way to carry out SO_2 and NO_x emission caps and trading systems under the regional total emissions gap. In this case, plotting several large regions and formulating the total SO_2 and NO_x emission ceilings, as well as relevant policies, will be very crucial for successful implementation [127].

6. Discussion

China’s fast growing economy brought about rapidly increase of energy consumption. Fossil energy still possessed absolute share of the total energy consumption although the energy mix had been slightly improved in the study period. Energy efficiency

was generally improved in fluctuation during this period, and this also reflects the inconsistency of energy-related policies and environmental measures at different stages. Generally, environmental cost was reduced due to improving energy efficiency and strengthening environmental measures. Impact of air emissions slightly declined in the study period due to a great deal of air environmental investment. Emergy loss had absolute share in impact of air emissions, which mainly came from small particle size dust (such as PM_5, $PM_{2.5}$). However, SO_2 and CO_2 should be emphasized due to their increasing impact in the later period. The fact that the performance of air environmental protection investment was obviously reduced reveals that the relatively low efficiency of the environmental protection investment in air field, and this may lie in unreasonable distribution among different areas, abnormal operation of environmental protection facilities, and abuse of investment due to lacking of effective supervision of governmental departments at all levels especially in the 10th Five-Year Plan.

This whole study period has been across the 10th Five-Year Plan and the 11th Five-Year Plan. Different strategies had been adopted to deal with the relationship between environmental protection and economic growth at the two stages [122]. The tensions between the growth imperative and sustainability have been in evidence throughout the two five-year plans. The State Council criticized the result of the10th Five-Year Plan as follows: "There is no breakthrough in some in-depth environmental issues that should have been addressed during the '10th Five-Year Plan'. There is no fundamental change in the inappropriate industrial structure and extensive economic growth mode. There are also such problems as environmental protection lagging behind economic growth, poor or inflexible mechanism, insufficient input and capacity. The phenomena of no strict observation of laws, little punishment to lawbreakers, poor law enforcement and supervision are still very common." Next, the government renewed its efforts to balance GDP growth and environmental protection in the 11th Five-Year Plan and stressed: "the transformation from focusing on economic growth ignoring environmental protection into putting equal emphasis on both. The authority takes the enhancement of environmental protection as an important tool to adjust economic structure and shift economic growth mode and seek development under environmental protection. The second is the transformation from environmental protection lagging behind economic growth into the synchronization of environmental protection and economic development… thus changing the situation of pollution followed by treatment, or destruction going along with environmental control. The third is the transformation from mainly employing administrative methods to protect the environment into comprehensive application of legal, economic, technical and necessary administrative methods to address environmental problems."

To direct it economic development towards a healthier and sustained growth path, the central government has set specified-energy targets' in the 11th and 12th FYPs. It tries to incorporate new policies on energy consumption and conservation into the overall economic development blueprint to achieve a total transformation of China's economic structure and a reduction in environmental pollution. However, for a country like China, there is hardly any single approach to meet rising energy demand and protect the environment at the same time. The serious situation is challenging the relationship between energy supply and GDP growth [128]. Since China has always insisted on relying mainly on domestic supply for the primary energy resources, it is necessary for the country to more rapidly develop its non-fossil energies.

In this case, renewable resources should play a much more important role in the coming decade. Nevertheless, due to expensive cost caused by grid constraints, insufficient long-distance transmission infrastructure and immature technology, China's large-scale implementation of renewable energy strategy remains challenging [129]. Compared with the priced for coal-fired plants, despite their relatively cleanness, it seems that coal will continue to be the primary energy resource in China in the foreseeable future.

Therefore, in the short to medium terms, China should encourage the deployment of advanced-coal technologies to mitigate the serious environmental issue caused by coal consumption effectively, such as coal gasification, liquefaction and carbon capture and storage. To help electricity price generated by renewable engines to compete with traditional fossil resources, extensive policy support and law enforcement are needed, such as adopting suitable fiscal and tax measures and increasing public R&D and information support [130]. In addition, the market entry barriers should also be removed to allow free competition among the companies. As far as air environmental protection is concerned, it may be a cost-effective way to carry out main air pollutants emission caps and trading systems under the regional total emissions gap. Moreover, China's government should further improve energy and environment-related policies and the corresponding supporting measures, and keep them consistency as far as possible. To ensure the implementation of the countermeasures, China's governments at all levels should strengthen supervision of economic activity in future.

Impact of emissions includes many aspects, and the considered factors are just part of them. Therefore, the real impact may be underestimated. However, the considered factors are the main aspects, and the proposed results can still provide beneficial suggestions for policy-makers.

The proposed methods can preliminarily assess the impact of emissions in an area or country. The indicator *RNR* reflects the energy mix, the *EUPG* gives the energy intensity of economic activity, the *ECPG* measures environmental cost per unit economic output, the *IEPEC* reflects environmental loading intensity of energy consumption, and the *EBPEI* embodies the performance of environmental protection investment. And they can form a set of useful tool for evaluating the relationships among economic growth, energy consumption, impact of emissions and environmental protection investment in an area or country.

7. Concluding remarks

(1) Energy consumption continues to quickly increase with fast economic growth in China, the energy mix has slight improvement, and energy efficiency is obviously enhanced but lagging behind the pace of economic growth during 2000–2007;
(2) Impact of air emissions does not increase with economic and energy consumption growth in the study period;
(3) Air environmental cost per unit economic output is effectively controlled in the study period;
(4) The performance of air environmental protection investment obviously decreased in the study period.

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